Dating precariously balanced rocks in seismically active parts of California and Nevada

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ABSTRACT

Precariously balanced boulders that could be knocked down by strong earthquake ground motion are found in some seismically active areas of southern California and Nevada. In this study we used two independent surface-exposure dating techniques—rock-varnish microlamination and cosmogenic ^{36}Cl dating methodologies—to estimate minimum- and maximum-limiting ages, respectively, of the precarious boulders and by inference the elapsed time since the sites were shaken down. The results of the exposure dating indicate that all of the precarious rocks are >10.5 ka and that some may be significantly older. At Victorville and Jacumba, California, these results show that the precarious rocks have not been knocked down for at least 10.5 k.y., a conclusion in apparent conflict with some commonly used probabilistic seismic hazard maps. At Yucca Mountain, Nevada, the ages of the precarious rocks are >10.5 to >27.0 ka, providing an independent measure of the minimum time elapsed since faulting occurred on the Solitario Canyon fault.

INTRODUCTION

Purpose and Scope

Balanced rocks, variously referred to as loganstones, logging stones, balancing rocks, and perched boulders (Twidale, 1982), are reported in the literature dating back to the 18th century (Hassenfratz, 1791). In reconnaissance-level searches of bedrock terrain in California and Nevada, one of us (Brune) found balanced rocks in many types of lithologies where they evidently evolved by natural processes. Brune (1996) described rocks that could be overturned by relatively little horizontal force as “precarious,” and he proposed that such rocks could effectively serve as low-resolution seismoscopes that operated over long periods of geologic time. Numerical modeling and dynamic field testing by Shi et al. (1996) and Brune (1996) indicated that precarious rocks could be toppled by accelerations of about 0.2–0.3 *g*.

We are unaware of any previous efforts to numerically date precarious rocks in seismically active areas. Brune and Whitney (1992) and Brune (1996) speculated that the rocks were on the order of thousands of years old on the basis of dark rock-varnish coatings. New surface-exposure dating methodologies now provide an opportunity to estimate the ages of the rocks. Here we utilize two independent dating applications—rock-varnish microlamination layering and cosmogenic ^{36}Cl dating—to estimate numerical ages for precarious boulders at three localities (Fig. 1): the granitic hills and pediments near Victorville and Jacumba, California, and the volcanic tuff cliff rocks at Yucca Mountain, southern Nevada.

METHODOLOGY

Geomorphic Model

A geomorphic model that accounts for the natural evolution of the precarious boulders is essential for confidently interpreting dating results (Nishiizumi et al., 1993). At Victorville and Jacumba, the precarious rocks are found among thousands of spheroidal granitic boulders derived from exhumed Mesozoic plutons (Oberlander, 1972). Through a classical two-stage, fracture-controlled weathering process (Twidale, 1982; Fig. 2), granitic corestones are left stacked in quasi-stable positions as the loose weathered granite is eroded. At Yucca Mountain, similar fracture-controlled processes have produced precarious blocks and columnar stacks of volcanic tuff on weathered cliff faces.

The balanced rocks we sampled for dating consisted of paired sets in which a precarious boulder was perched on top of a more stable pedestal. In each case, we visually examined the precarious rock, the pedestal, and the basal rocking surfaces for weathering-rind and rock-varnish characteristics that would confirm both relative age and long-term unstable geometry of the set.

Rock Varnish

Rock varnish is a ubiquitous, dark, Fe- and Mn-rich coating as thick as 200 µm that accretes on subaerial rock exposures in arid and semiarid

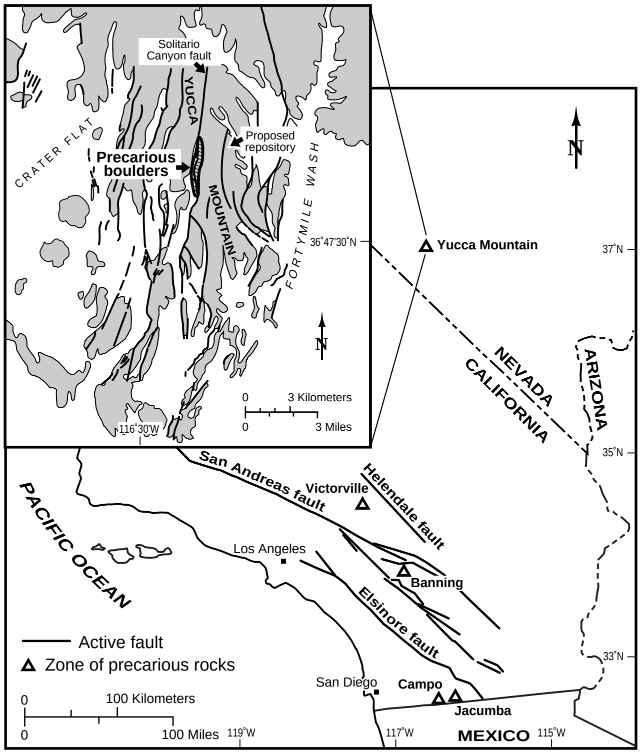

Figure 1. Location maps showing precarious rock sites and seismically active faults at Victorville and Jacumba sites in southern California, and Yucca Mountain, Nevada.

Data Repository item 9857 contains additional material related to this article.

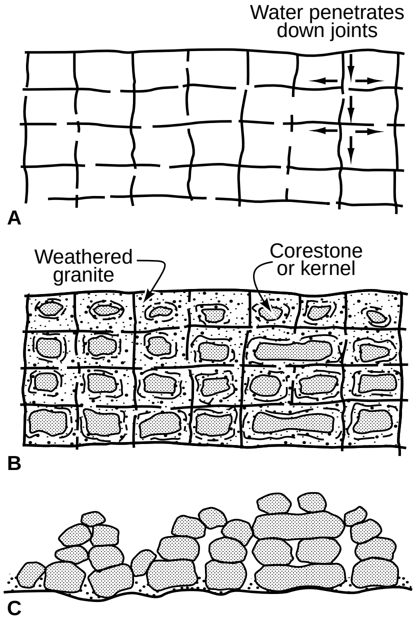

Figure 2. Two-stage development of precariously balanced rocks. In first stage, meteoric water infiltrates fractured rock (A) and grüs develops around corestones (B). In second stage (C), grüs is eroded, leaving corestones stacked in precarious positions (modified from Twidale, 1982).

TABLE 1. ROCK VARNISH MICROLAMINATION ANALYSES

Boulder name	Microlamination layering age (radiocarbon years, ka)	^{36}Cl age from Table 2 (calendar years, ka)
Victorville		
Skyline #1	>10.5**	49.2**
Skyline #2	>21.0*; >21.0**	61.0**
Rich II	>10.5 - <14.5*; >10.5 - <14.5**; >21.0**	15.0*
R^3	>10.5*; >10.5 - <14.5*; >10.5**	
TL-1	>10.5*; >14.5 - <21.0*; >10.5**	
TL-2	>10.5*; >10.5 - <14.5**	
JB-2	>10.5 - <14.5**	
Jacumba		
Steve Day 2	>10.5*; >21.0*; >14.5**; <10.5**	23.6**
Steve Day 3	>10.5**; >10.5**; >10.5**; >10.5**	
Yucca Mountain		
Pillow	>10.5**; >21.0*	
Cliff	>14.5**	
Redeye	>27.0 - <35.0**	
Sue	>10.5**	
Whitney	>10.5 - <14.5*	
Len	>10.5 - <14.5**	
Tripod	>10.5**	
Doozey	>10.5**	
Honeycomb	>10.5**	

Note: Sample ages interpreted from layering units microscopically identified in ultra-thin section.

*Precarious rock face sample.

**Pedestal rock face sample.

environments. Several techniques are available for surface-exposure dating by rock-varnish methodologies (cf. Oberlander, 1994). In this study we used the experimental varnish microlamination dating methodology (Dorn, 1990; Liu, 1994; Cremaschi, 1996; Liu and Dorn, 1996). This methodology is based on the earlier findings by Perry and Adams (1978) that rock varnish consists of alternating Mn-rich and Fe-rich (Mn-poor) microlaminations that appear to record paleoclimatic signals; black Mn-rich and yellowish-orange Mn-poor layers are correlated, respectively, with oscillating episodes of humid (low alkalinity) and arid (high alkalinity) climatic conditions (Dorn, 1990; Jones, 1991).

Rock-varnish samples were collected from multiple locations on the vertical faces of the precarious-pedestal rock sets. Ultra-thin (<5–10 µm) polished sections of the varnish were examined using a conventional transmitted light microscope at magnifications of 400–1200×. The microlamination sequences were interpreted on the basis of the layering unit (LU) results of Liu and Dorn (1996; Fig. 3); i.e., major black layers are correlated with pulses of climatic cooling and wetness. The uppermost layer of all rock varnishes (LU-1) is universally Mn poor, reflecting the dry, alkaline conditions of the Holocene. Pre-Holocene varnishes are characterized by one or more black, Mn-rich layers reflecting more humid climates. The first major black layer encountered below LU-1 is correlated with the Younger Dryas climatic event (10.5 ka) on the basis of global evidence (cf. Broecker, 1994) and on the basis of paleoclimatic evidence for a Younger Dryas event in the southern Great Basin (Quade et al., 1998). Successively lower black layers are correlated with Heinrich events H1 (14.5 ka), H2 (21.0 ka), H3 (27.0 ka), and H4 (35.0 ka).

Cosmogenic ^{36}Cl

The accumulation of cosmogenic ^{36}Cl in rocks exposed to cosmic radiation at the ground surface can be used to calculate the surface-exposure age of the rocks (Phillips et al., 1986). Cosmogenic nuclide accumulation is a function of exposure time, geographic and altitudinal location, and abundance of target elements. By measuring the isotopic composition of the host rock, and by applying a predetermined production rate, the apparent surface-exposure age of the rock can be calculated.

In this study we collected samples at Victorville and Jacumba from some of the same rock faces sampled for rock varnish. Two additional samples were collected from unvarnished rocks at Campo and Banning (Fig. 1). Major element and isotopic ^{36}Cl analyses were determined according to procedures described by Zreda et al. (1991). We used the production rates at sea level and high latitudes reported by Phillips et al. (1996) and scaled them to our sample locations. Erosion-corrected surface ages were calculated using the approach of Phillips and Plummer (1996). The effects of topographic shielding on production rates were estimated using the integral from Zreda and Phillips (1994a).

RESULTS AND DISCUSSION

We analyzed 24 rock-varnish samples from the Victorville and Jacumba rock sites, and 10 samples from Yucca Mountain. Rock-varnish layering unit ages were estimated for each sample (Table 1); detailed descriptions of layering sequences are in the GSA Data Repository.[1]

Our results show that the uppermost microlamination in all samples is the yellowish-orange, Mn-poor Holocene layer LU-1. At least one major black layer was found beneath this uppermost layer in all but one of the varnish samples. The first-encountered black laminations are correlated with LU-2, and successively lower black layers are correlated with LU-4. The presence of a major, black, Mn-rich microlamination below the upper Holocene layer thus indicates that the varnish has undergone at least one wet climatic cycle. If this first black layer represents the Younger Dryas event, then all of the precarious rocks examined in this study are at least 10.5 ka.

We interpret the rock-varnish ages to be minima because of the lag time in varnish accretion and the polycyclic nature of the weathered rock faces. The ages of the Victorville rocks range from >10.5 ka to >21.0 ka (Table 1), and several rocks are between >10.5 ka and <14.5 ka on the basis of the presence of a single black layer and a

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[1] Data Repository item 9857, varnish microlamination descriptions and analyses of ultra-thin sections, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

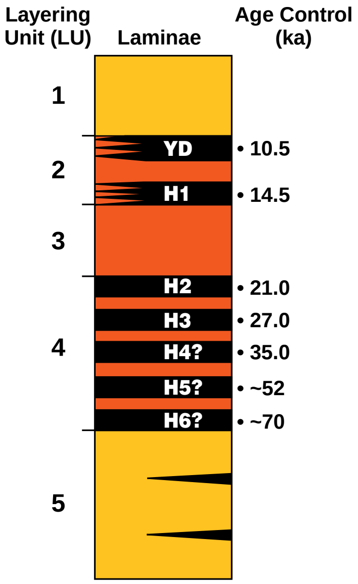

Figure 3. Idealized sequence of varnish layering units (LU) from Liu and Dorn (1996) showing correspondence to dated Heinrich events from Broecker (1994).

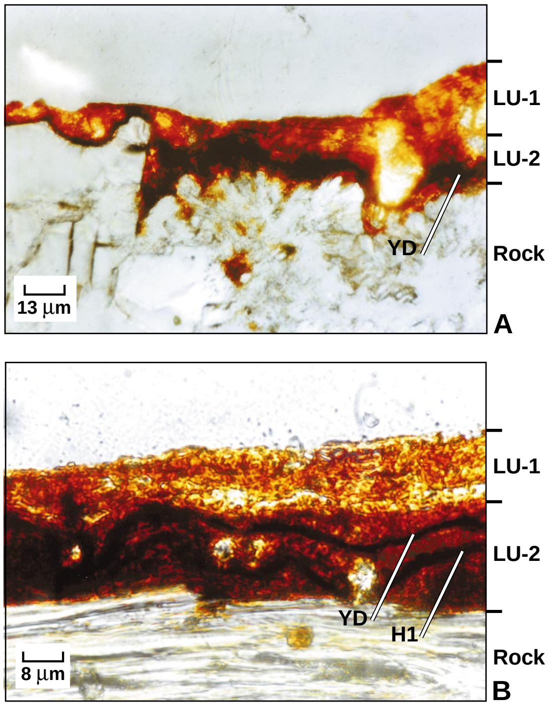

Figure 4. Rock-varnish ultra-thin sections showing microlamination layering. A: Rock Len at Yucca Mountain. LU-1 is yellow-orange layer on top, and LU-2 contains one black layer (YD) and basal orange layer indicating that sample is >10.5 ka to <14.5 ka. B: Rock Steve Day #2 pedestal face at Jacumba. Top orange layer is LU-1 and two black layers beneath it are YD and H1 in LU-2, indicating that sample is >14.5 ka.

basal orange layer (Fig. 4A). The microlamination ages of the two Jacumba precarious rock sets are similar, ranging from >10.5 ka to >21.0 ka. Minimum rock-varnish ages of Yucca Mountain rocks are largely between >10.5 ka and <14.5 ka, although some rocks may be >21.0 to >27.0 ka on the basis of the presence of LU-4.

Cosmogenic ^{36}Cl ages were determined for seven precarious rock sets in southern California (Table 2). The rocks range in apparent age from 15 to 72 ka, depending on the assumed erosion rate (ε) of the rock face. Thick weathering rinds and dark varnish on the rocks suggest that surface erosion has been negligible, and the $\varepsilon = 0$ rate is assumed to best approximate the actual cosmogenic ages. The ^{36}Cl ages are interpreted as maxima because of the uncertainties associated with the burial and exhumation histories of the rocks (Zreda and Phillips, 1994b).

Four rocks at Victorville and Jacumba were dated by both rock-varnish and ^{36}Cl methodologies (Table 1). The rock R^3 (Fig. 5A) yielded a ^{36}Cl ($\varepsilon = 0$) age of 15.0 ka, an age in reasonably close agreement with the rock-varnish ages between >10.5 and <14.5 ka. The precarious rock face from Steve Day #2 (Fig. 5B) provided similar ^{36}Cl (23.6 ka) and rock-varnish (>21.0 ka) ages. The ^{36}Cl ages for Skyline #2 and Rich II are substantially older than the respective rock-varnish ages, a difference possibly related to either pre-varnish spalling of the rock face or to inherited ^{36}Cl.

CONCLUSIONS AND IMPLICATIONS FOR SEISMIC HAZARD STUDIES

On the basis of rock-varnish and cosmogenic ^{36}Cl dating, we conclude that the precarious rocks have been exposed for at least 10.5 k.y., a minimum exposure age qualitatively supported by the thick, polycyclic weathering rinds and dark rock-varnish coatings found on the rock surfaces. The results further indicate that the precarious rocks at Victorville and Jacumba have not been subjected to earthquake ground accelerations greater than 0.2–0.3 g in more than 10.5 k.y., possibly longer if the older varnish and ^{36}Cl ages are close to the actual ages. The Victorville site is located between the active San Andreas (35 km west) and Helendale (15 km east) faults, and the Jacumba site is located about 18 km from the southern end of the

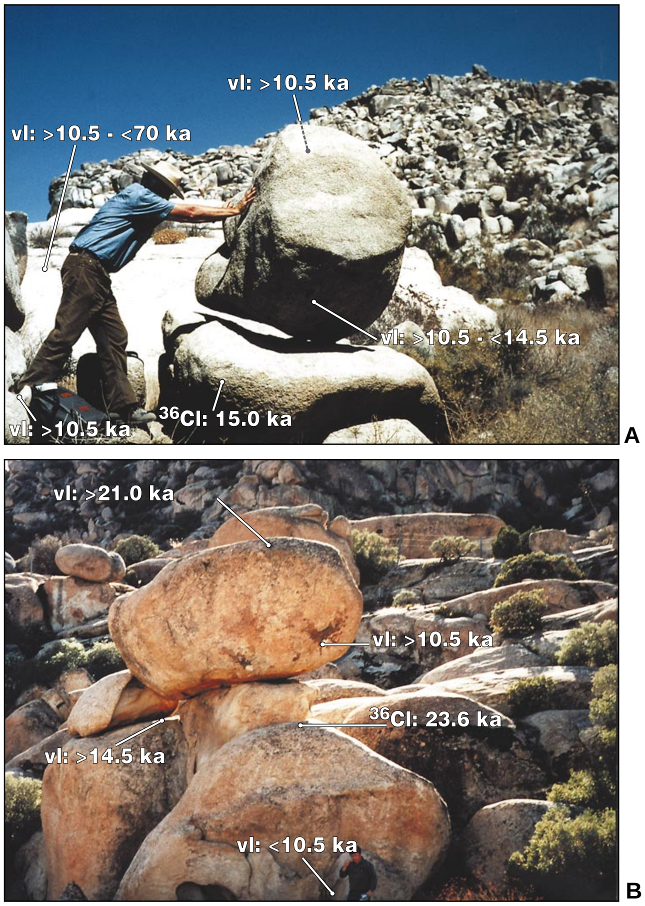

Figure 5. Location of rock-varnish microlamination (vl) and ^{36}Cl sample ages for rocks R^3 (A) and Steve Day #2 (B).

TABLE 2. RESULTS OF ^{36}Cl ANALYSES

Boulder	Latitude (°N)	Longitude (°W)	Elevation (m)	Cl (ppm)*	^{36}Cl/10^{15}Cl	Boulder age (ka)†	
						ε = 0 mm/yr	ε = 5 mm/yr
R^3	34.5825	117.3156	930	14	700 ± 30	15.0	15.3
Split Rock	34.5528	117.2840	853	11	1660 ± 160	57.8	68.9
Skyline #2	34.5489	117.2851	811	7	2220 ± 40	49.2	58.6
Rich II	34.5555	117.2711	951	14	1250 ± 60	61.0	71.8
Steve Day #2	32.6611	116.2056	853	6	1220 ± 40	23.6	25.3
Campo	32.6278	116.4417	829	35	270 ± 50	34.0	32.4
Banning	33.8519	116.8285	1341	21	290 ± 20	13.0	13.0

*Cl concentrations rounded to nearest 1 ppm.

†Boulder ages rounded to nearest 0.1 ka and reported for two boulder surface erosion rates (ε). Combined analytical and production rate errors in ages estimated at 15% - 20%.

Elsinore fault (Fig. 1). Brune (1996) noted that the presence of precarious rocks in these areas appears to conflict with probabilistic seismic hazard maps that show >0.5 g at these sites for time periods of 1–5 k.y. (cf. Working Group on California Earthquake Probabilities 95, 1995), and he suggested that the rocks illustrate that the hazard in some parts of southern California is not as high as predicted by these seismic hazard models.

At Yucca Mountain, the precariously balanced rocks lie on the footwall of the late Quaternary Solitario Canyon fault, which bounds the west margin of the proposed high-level nuclear waste repository (Fig. 1), and they provide an independent constraint on the recent strong ground motion at the site. The rock-varnish exposure ages of these rocks suggest that large earthquakes have not occurred on the Solitario Canyon fault for >10.5 to >27.0 k.y., an elapsed time consistent with the paleoseismic history of the fault. Ramelli et al. (1996) concluded that the most recent faulting event on the Solitario Canyon fault occurred between 20 and 30 ka.

The preliminary results of this study demonstrate that the surface-exposure ages of precariously balanced rocks can be successfully used to estimate the elapsed time since strong ground motion occurred at the rock sites. In contrast to paleoseismic trenching studies, which only pinpoint sites of fault rupture, precarious boulders may provide direct, far-field evidence of earthquake occurrence. If the evolutionary history of a precarious rock can be established using a viable geomorphic model and demonstrable evidence of long-term precarious geometry, surface-exposure dating has the potential to provide a new paleoseismic tool for use in characterization of regional seismic hazard.

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